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14. ABSTRACT
This project studied firm-level capabilities in China for technology innovation in several energy-related domains: civilian nuclear power, wind turbine manufacturing, and solar photovoltaic panel fabrication. The research documented patterns of knowledge creation, transfer, and dissemination between Chinese and overseas firms, as well as among Chinese firms themselves. The research also examined the interaction between Chinese firms engaged in energy-related innovation and Chinese governmental agencies conducting various aspects of industrial policy. The research addressed policy concerns surrounding China's technology capabilities, as well as China's

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Report Title

Final Report: China's Emerging Capabilities in Energy Technology Innovation and Development

ABSTRACT

This project studied firm-level capabilities in China for technology innovation in several energy-related domains: civilian nuclear power, wind turbine manufacturing, and solar photovoltaic panel fabrication. The research documented patterns of knowledge creation, transfer, and dissemination between Chinese and overseas firms, as well as among Chinese firms themselves. The research also examined the interaction between Chinese firms engaged in energy-related innovation and Chinese governmental agencies conducting various aspects of industrial policy. The research addressed policy concerns surrounding China's technology capabilities, as well as China's ability to acquire knowledge through participation in global supply chains for high-technology products. The work also addressed theoretical issues surrounding the role of innovation in industrial development more generally, effectively arguing that the contemporary Chinese experience suggests a new form of late industrialization in which innovation surrounding late-stage technology commercialization plays a vital role. Methodologically, this project developed original qualitative data collected primarily at the firm level both within China and globally. Data were collected primarily through participant observation and semi-structured interviews. Our empirical data suggest that China-based firms in the renewable energy domain – namely in wind turbine production and solar PV cell/module fabrication -- have developed a unique form of innovative manufacturing, one based on the simultaneous management of tempo, scaling, and cost reduction. For particularly complex energy technology systems, such as civilian nuclear power plants, the greatest challenges involve not new technology development, but rather systems integration. In these domains, Chinese firms have not necessarily achieved significant advances. Moreover, experience in China has helped multinational systems integrators move into new domains of IT innovation, remote sensing, data management, and industrial software development.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/21/2015	5.00	Jonas_Nahm, Edward_Steinfeld. Scale-up Nation: China's Specialization in Innovative Manufacturing, World Development, (02 2014): 288. doi:
TOTAL:	**1**	

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received		Paper
09/05/2014	6.00	Edward_Steinfeld, Troels_Beltoft. Innovation Lessons from China, MiT Sloan Management Review, (06 2014): 49. doi:
TOTAL:	**1**	

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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TOTAL:

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Received	Paper

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(d) Manuscripts

Received	Paper	
08/22/2013	1.00	John Deutch, Edward S. Steinfeld. A Duel in the Sun: The Solar Photovoltaics Technology Conflict Between China and the United States, MiT Energy Initiative Special Report (03 2013)

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Number of Manuscripts:

Books

Received Book

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Received Book Chapter

08/22/2013 3.00 Florian Metzler, Edward S. Steinfeld. Sustaining Global Competitiveness in the Provision of Complex Products and Systems: The Case of Civilian Nuclear Power Technology, Cambridge, MA: MIT Press, (09 2013)

08/22/2013 4.00 Edward S. Steinfeld, Jonas Nahm. THE ROLE OF INNOVATIVE MANUFACTURING IN HIGH TECH PRODUCT DEVELOPMENT: EVIDENCE FROM CHINA'S RENEWABLE ENERGY SECTOR, Cambridge, MA: MIT Press, (09 2013)

TOTAL: **2**

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Jonas Nahm	1.00	
Florian Metzler	0.20	
FTE Equivalent:	**1.20**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Edward S. Steinfeld	0.67	
FTE Equivalent:	**0.67**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Jonas Nahm
Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

This research effort was motivated by a series of both applied and conceptual questions surrounding China's rise as a global industrial power, especially in high technology areas. Focusing on the energy technology domain, this research explored how China's deployment of new, state-of-the-art technology systems -- and how the Sino-foreign commercial partnerships surrounding their development -- can inform our understanding more generally of China's emerging industrial capabilities. The research was able to demonstrate empirically what types of innovation were taking place in Chinese firms, the mechanisms through which innovation proceeded both within and across firms, and the manner by which knowledge was generated and transferred.

More fundamentally, the research was able to use an examination of China's energy technology boom to challenge established theories of late development and industrial catch-up. As this research project has argued, the Chinese experience forces us to re-conceptualize the role that innovation plays in contemporary development, not just in advanced industrial societies, but also middle-income and poorer nations. Chinese patterns of innovation also suggest that we are in the midst globally of a new industrial revolution, one that is re-ordering patterns of innovation and value creation across not just the developing world, but also in advanced industrial societies. As indicated by our findings in the energy domain, Chinese firms are in many ways catching up with regard to manufacturing-related innovation. At the same time, they have arguably fallen even farther behind US and European counterparts in terms of the information technology, digital design, product lifecycle planning, and simulation systems upon which value in high tech industry is increasingly concentrating.

This project -- a comprehensive study illuminating in fine-grained detail the technology development processes that take place within Chinese energy firms and across China's emerging high tech innovation ecosystem -- represents a first-of-its-kind achievement. Owing to a number of reasons, including the difficulty of gaining access to firms, the degree of cultural awareness required to build trust with respondents, the language skills required to conduct in-depth qualitative research, and the general secretiveness surrounding information in Chinese governmental and business circles, the degree of difficulty for accomplishing this type of research is extremely high. As indicated by our publication record, however, our team has achieved a number of successes across a wide variety of technology domains, including wind turbine manufacturing, solar PV fabrication, and civilian nuclear power technology design and deployment.

Our main findings are as follows:

1. China-based firms have indeed developed a unique form of innovative manufacturing, one based on the simultaneous management of tempo, scale, and cost reduction.

2. This form of innovative manufacturing is centered on engineering capabilities residing at the intersection between upstream R&D (generally conducted by foreign firms based outside China) and downstream fabrication (generally occurring within China).

3. Much of this innovation is being applied not just to mature products and product platforms, but to frontier technologies and new-to-the-world energy systems.

4. China-based innovative manufacturing takes place not simply within the single firm, but across firm-level boundaries in complex multinational production and R&D networks. In this sense, the Chinese developmental trajectory looks dramatically different from what was observed in earlier decades in Japan and South Korea, where firms tended to be more vertically integrated, more self-contained, and far less immersed in global production networks.

5. The learning that takes place in these networks, rather than flowing unidirectionally (i.e., from foreign technology leaders to Chinese duplictors), flows multidirectionally and recursively.

6. For particularly complex, capital intensive energy technology systems, such as civilian nuclear power plants, the greatest challenges often involve not so much new technology development (a considerable amount of technology "lock in" obtains), but rather challenges surrounding systems integration. It is in the area of systems integration that some of the most important achievements surrounding cost reduction, safety, and reliability can be realized. In these domains, Chinese firms have not necessarily achieved significant advances, even as the most advanced technology systems are being deployed on Chinese soil. Many of the leading firms in systems integration activities continue to be foreign, and especially from advanced industrial nations. Moreover, the experience in China has helped multinational systems integrators move into new domains of information technology innovation, remote sensing, data management, and industrial software development. It is conceivable that these areas will actually become increasingly important in manufacturing-related domains as well, especially if predicted trends play out with respect to "smart" manufacturing, the "internet of things," additive manufacturing, or -- in European parlance -- "Industry 4.0." In other words, what this study has observed with respect to systems integration in areas such as civilian nuclear power technology deployment may very well become the norm in manufacturing domains as well.

This study's findings are based on fieldwork that included the following:

-- 119 interviews in China in the wind power and solar PV industries

-- An additional 117 interviews were conducted with participants in the wind and solar power-related production networks in Europe and the United States
-- 79 interviews in the Chinese nuclear power sector, including both Chinese indigenous and multinational firms
-- Additional corroborative interviews were conducted with technology firms operating outside the energy sector (including in optics, electronics, and machinery fabrication), as well as with public officials and academics in China

Through the course of our fieldwork, our interview protocol involved asking respondents to trace the path by which the technologies they work on move from initial R&D phases through ultimate product development and deployment. Respondents were asked to identify the parts of the process in which their firms concentrate, the nature of their relationships with other firms focused on other stages of the technology development process, and the nature of the knowledge that they believe to be core to their firm's competitiveness. Respondents were asked to describe with reference to specific examples their interactions with technology collaborators, be they joint-venture partners, suppliers, subcontractors, or customers. Respondents were also asked to identify specific challenges, problems, and successes encountered during the technology development and deployment process. A series of follow-on questions then explored the kinds of inputs required by the firm to achieve competitiveness in its given domain, as well as the strategies employed to acquire those inputs. In some cases, respondents were willing to discuss the specific types of skills required of their firm's workforce, as well as the modes by which those skills are developed. Interviews were also able to delve into issues of the specific types of technical capabilities required to innovate, the particular types of partners and suppliers that are most conducive to innovation and knowledge development, and the types of investment inputs most likely to generate knowledge, whether managerial or technical in nature.

As noted, our empirical findings have permitted us to define and categorize the phenomenon of Chinese innovative manufacturing, as well as the broader, non-China-specific concept of innovation-centric late development. We have also at least begun to understand the connections between innovation in China and innovation in advanced industrial nations, including the United States. At minimum, we have demonstrated that the knowledge flows and learning are not unidirectional, and that there are far more complex phenomena unfolding than simply technology transfer, duplication, and mimicry.

Our work has opened up a series of new avenues which require further empirical exploration and conceptualization. Our areas of focus included both primarily electromechanical and electrochemical processes. It is conceivable that substantial differences in terms of degree of production process codification and nature of learning exist across these categories, but in this particular project, our empirical work did not focus on this distinction. We intend in future work to explore more deeply the differences between electromechanical and electrochemical processes, especially when they coexist within single industrial domains (as they do, to some extent, in the solar PV area, as well as certain types of civilian nuclear power componentry, including zirconium cladding.

In terms of follow-on work, we also believe that while we have defined several phenomena (i.e., Chinese innovative manufacturing, innovation-centric late development, and IT-intensive systems integration) and begun to map networks, we still need to deepen our understanding of the precise mechanisms and processes by which learning takes place across firms. We believe future work must combine our existing interview techniques with new modes of process tracing, effectively entailing ethnographic techniques directed toward understanding the experience of single firms within the wind, solar PV, and civilian nuclear sectors. Such ethnographic analysis will prove critical for understanding relationships between firms involved in joint technology development efforts. Such analysis, when conducted comparatively across similar firms engaged in similar types of activities, will also allow us to compare relative capabilities between firms operating across different ecosystems or originating from different nations. We specifically hope in future work to pursue direct comparisons between China-based solar PV fabricators and US-based counterparts. We intend to do the same in the wind and civilian nuclear power sectors. In a sense, our model for this type of comparative industrial ethnography is that set out by Ronald Dore in his seminal work "British Factory-Japanese Factory" (1973).

We recognize that the technology development phenomena that this study examined -- and that we will continue to work on in future projects -- are complex and unfold sequentially over time. Neither static nor one-step in nature, these evolutionary processes often defy simple input-output analysis. Drawing causal or even descriptive inferences under such conditions is challenging. We believe, though, that this project has demonstrated that through comparative case analysis and fine-grained qualitative data collection, we can push the research agenda forward and open up new areas of empirical and conceptual inquiry.

Though there is still much work to be done, this project has expanded our understanding of the conditions under which the geography of technology development and deployment drives the location of innovation-intensive and knowledge-intensive activities. We have also expanded our understanding of the circumstances in which at least in some industrial domains, higher-value innovation activities remain separated from physical fabrication, while in other domains, upstream innovation and downstream fabrication and scaling remain inextricably linked. And, finally, we have furthered our understanding of the conditions under which advanced industrial incumbents either lose or expand knowledge-based sources of competitive advantage as markets increasingly move to developing or middle-income locales across the world.

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Technology Transfer